Arnold Schwarzenegger
Governor

MAINTAIN, ENHANCE AND IMPROVE RELIABILITY OF CALIFORNIA'S ELECTRIC SYSTEM UNDER RESTRUCTURING

APPENDIX - XVI

Integration of Distributed Technologies - Standard Power Electronic Interfaces

PIER FINAL PROJECT REPORT

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Integration of Distributed Technologies – Standard Power Electronic Interfaces

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Integration of Distributed Technologies – Standard Power Electronic Interfaces

Summary

Distributed technologies are slated to represent a substantial portion of future additions in power generation capacity. Modern distributed generation technologies such as microturbines, fuel cells and photovoltaic systems invariably employ several power electronic converters such as rectifiers and inverters in them in order to provide utility grade ac power. The cost of power electronic systems represent a substantial portion of overall installation costs. This has been due to the complexity of the engineering and realization of power electronics system packaging.

Ongoing investigations at the Center for Power Electronics Systems are aimed at realizing a ten-fold improvement in the performance of power electronics systems through the development of integrated power electronic modules. These integrated power electronic modules can be used as a building block for various power electronics products. This report presents the results of ongoing investigations on development of high power electronic systems for distributed generation systems using integrated power electronic modules. The investigations have focused on developing a modular architecture that would allow using multiple power converters rated at small power levels to realize higher power systems in a systematic manner.

Bricks & Buses has been developed as a concept for realizing scalable power converter modules that would integrate the design domains involving electrical, thermal and mechanical design features. Examples of realizations using the proposed concept are presented. Geometric design tool development process that would enable the realization of the proposed architecture is outlined in the report.

Further investigations are continuing on developing prototype power converters using the Bricks and Buses concept and benchmarking a design process using commercial computer software.

Integration of Distributed Technologies – Standard Power Electronic Interfaces

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1. Introduction

Electric Power Research Institute's technology roadmap projects a need for additional of electrical generation capacity of 10,000 GW in the next 50 years across the globe [1]. The situation of electrical energy infrastructure in the US as well as in the developing world has become highly tentative due to the unleashing of the deregulation in the industry. The current market scenario is continually and painfully under strain to adjust itself to the trends in energy supply and demand. In order to enable these conditions to reach a vibrant and dynamic equilibrium, there is a strong need by generation agencies to react to the market trend in an agile fashion to add generating capacity to face high demands. Regulatory barriers with due regard to emission, location and political considerations make it difficult to add generating capacity fast enough to react to the marketplace. Conventional generation systems take years to reach the stage of commissioning since conception. However, distributed electric power generation systems are well suited to meet such needs in a rapid manner. These generation systems are small, highly efficient, fast to commission and feature lower emissions. US Department of Energy has set a goal of 20% of addition of generating capacity within the next decade to occur from distributed power generation systems [2].

Distributed generation systems include renewable energy sources such as photovoltaic, and wind turbines as well as emerging advanced fossil fuel generation systems such as microturbines and PEM fuel cells. A majority of these systems consists of a dc bus fed by the primary energy source directly or through a rectifier. The energy from the dc bus is converter into utility grade ac waveforms to feed typical domestic and industrial loads. Thus, power electronics represents a critical constituent technology for distributed generation systems. In the projected scenario of 20% of future capacity additions from distributed generation, the power converters employed therein represent approximately 2,000 GW of potential throughput.

Distributed Generation (DG) systems may incorporate different primary electricity generation technologies such as conventional fossil fuel based alternators, wind turbines, photovoltaic cells, fuel cells or micro-turbines. Numerous positive features of micro-turbine based generators are making them more attractive compared to conventional fossil fuel generators. It is therefore expected that a significant fraction of future DG systems will contain power electronic converters forming a critical interface between the primary electrical source and the utility interconnection at the point of load. The DG application demands that the power electronic converters be capable of reliable operation for over tens of thousands of hours and available at low cost. Although, power converter technologies for motor drive and computer applications have made significant advances in the past decades, there remain significant obstacles to be overcome in order for them to become effective in such applications sensitive to cost and reliability as automotive and distributed generation systems.

Power electronic converters generally represent a significant fraction of the cost of present day energy systems. This is generally true of several application areas of power electronic converters such as motor drives, telecommunication power supplies, electronic ballasts, etc. There are several reasons for this scenario. Traditionally, design and manufacturing of power electronic systems has taken place on an application specific basis. This has resulted in product specific designs with low volume and large overhead in development, engineering and tooling for manufacturing. The vision of Center Power Electronics Systems (CPES), a National Science Foundation initiated engineering research center of excellence is focused on the development an integrated systems approach to standardize power electronics components and packaging techniques in the form of highly Integrated Power Electronics Modules (IPEMs). The IPEM approach makes possible increased levels of integration in the components that comprise a power electronic system - devices, circuits, controls, sensors, and actuators. These components are integrated into standardized modules and subassemblies with improved manufacturability, which, in turn, are customized for particular applications. The strategic plan of CPES to develop a fully integrated, three-dimensional multi-chip power module that would realize a cumulative 10-fold improvement in performance and cost.

Currently, the core activities of IPEM development at CPES is focused to serve the motor drive applications and computers/telecom power supplies market. However, DG represents a tremendous opportunity for the application of power electronics systems to a play a vital and positive role on the supply side of electricity, just as they have, and continue to do so on the demand side. Such utility electric power applications are considered the future "roof" of the power electronics house, while the floor and walls are represented by current power electronics applications sector including power supplies and motor drives [3]. This project is aimed at developing and furthering links between CPES and the utility applications sector of the power electronics industry. This is achieved by leveraging the research objectives of CPES with those of California Energy Commission to play a crucial role in promoting the *IPEM inside* vision further in distributed generation applications.

In order for these IPEMs to be successfully applied towards providing power electronics solutions for DG systems, they will have to meet the demands of DS systems. In motor drives applications, the loads are typically dedicated, balanced and well characterized. In addition, the wiring is made one-time and rarely reconfigured. Protection coordination and fault management are made on that basis. However, the operating scenarios of distributed generation systems are vastly different and varying: they may be unbalanced; their nature diverse in terms of power factor, harmonics, cycling, start-up behavior, etc. Thus, it is to be naturally expected that the design of IPEM modules will have to incorporate all the design features necessary to operate reliably under these conditions.

The primary focus of the CPES demonstrative efforts are at modest power levels (about 3 kW), and scale up in power levels as the technological concepts mature. However, in order to increase the power levels higher as required in utility systems, one needs to develop strategies for operating multiple IPEM based systems together. Even if IPEM based design and manufacturing concepts become firmly established at higher power levels, in order to realize the power throughput levels required by electric utilities, strategies to increase the power levels further will be necessary. Technologies that deploy many lower power units together to realize higher power levels will be preferred over those that require custom designed higher power individual converters. This is due to the economical benefits that accrue from reduced engineering effort and high volume mass manufacturing. Hence, it is imperative to develop techniques for multiple parallel operation of ac power converters.

One of the key features to be investigated involves the integration of multiple units of lower power inverters to realize a larger power system in a modular fashion. In this fashion, larger power units (say 200 kW) may be realized using high volume lower power (say 20 kW) products at minimal additional engineering effort. The project will begin by performing a detailed study to the characteristics and capabilities of IPEMs currently under development. In parallel, the characteristics and capabilities required of IPEMs for applications in DG systems will be identified. The nature of loads in industrial distribution systems, faults in typical distribution systems, protection issues, synchronization issues, control issues, active and reactive power sharing, etc. will be taken into account during this process. Further to this study, a gap analysis will be performed to document the requirements of additional features to be composed into the IPEM design process to enable them to be applied in DG systems.

In particular, a modular approach to realizing high power inverter systems at utility rated power levels using multiple inverters rated at lower power level is being developed under the project. The approach will lead to the benefits of reduced costs and increased reliability realized through various projects under way in CPES to develop IPEMs and associated technologies to realize low cost power converters and inverters directly translating into distributed generation applications.

Operation of multiple power converters operating together to deliver increased power throughput has become well-established in the field of dc-dc converters. It has become the backbone of the distributed power systems concept in communications and computer industry. This project's technical activities will enable similar developments in the area of dc-ac power converters. However, the problems to be solved are more challenging due to the nature of ac systems. These challenges include:

- Multiple phases
- Active power balance
- Reactive power balance
- Frequency synchronization
- Phase synchronization
- Harmonic current balance
- Grounding issues
- Phase imbalance
- Line interconnection
- Multiple phase filter interactions

The activities in this project are aimed at addressing all these issues, develop and demonstrate a solution that will allow operation of multiple inverter systems in parallel to realize higher power levels in a truly distributed manner.

The above list of technical challenges represents "soft" issues related to control of the converter. Of even greater importance is the geometric design and manufacturing issues related to managing the complexity of inverter systems. This report documents the requirements of modular power converter building blocks for distributed generation systems. It sets guidelines for generating a roadmap for research and development efforts that will be useful for CPES, CERTS and other agencies to focus on lowering the cost and improving the reliability of power converters in DG systems. In next phase of the project, a proof of concept system will be demonstrated using hardware prototypes of IPEM based inverters.

This report is organized into six chapters. In Chapter 2, typical functional component elements that constitute advanced DG systems are described. State of the art means for realizing these functional elements and their technology trends are discussed in Chapter 3. In Chapter 4, an alternative modular architecture of realizing DG systems in particular and power electronic systems at large is presented. Various critical technology elements that constitute the proposed approach and the development activities necessary to make the approach viable are discussed in Chapter 5. A status of design tool development process is presented in Chapter 6. The final concluding chapter contains a brief summary of the results including a brief outline of work for the next phase of the project.

2. Advanced DG System Components

Advanced DG systems may draw their primary energy from such diverse sources such as wind, sun or fossil fuels. This may be gleaned from the simplified schematic illustrations of systems shown in Fig. 1. While the primary energy converter that converts various forms of energy into electricity are different in each case, balance of system (BOS) components are similar for all systems. Although the cost and reliability of the primary energy converter depend on constituent technology that is particular to the given form of DG system, the cost elements related to the BOS components are common to all the systems and is the main thrust of investigations in the project.

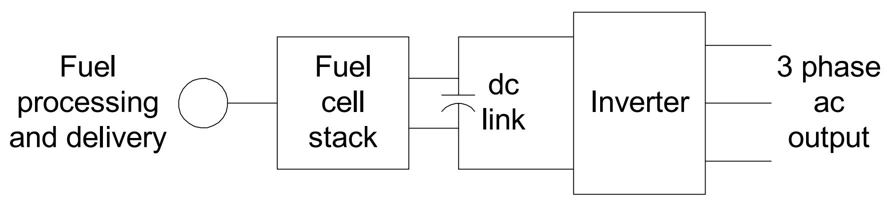

Fig. 1(a): Block diagram of fuel-cell power generation system

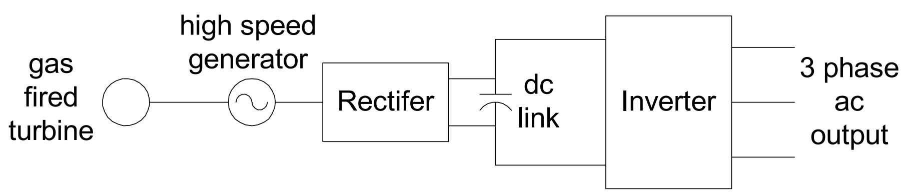

Fig. 1(b): Block diagram of micro-turbine power generation system

The following elements may be identified as being BOS elements that constitute advanced DG systems: (a) Source interface converter, (b) dc bus (c) inverter (d) output filter (e) interface transformer (f) interface protection elements and switchgear (g) sensors (h) system control/software (j) Interconnections. In order to systematically address the cost elements associated with BOS components it is worthwhile to study the state of the art of each of these and their interconnection technologies.

A. Source Interface Converter

The source interface converter is used to match the characteristics of the electric power output from the primary electrical energy source with the dc bus. In some simple low power DG systems, it may not exist at all. In its simplest form it may consists of a dc-dc converter that steps up or steps up a voltage to match that of the dc bus. This configuration is common in a fuel cell generation system. In a micro-turbine system, the ac output from a high-speed permanent magnet alternator is converter using a simple diode bridge rectifier or a bidirectional ac-dc converter, which may also function as a starter for the alternator/turbine system. In wind turbine systems, the converter may be responsible for maintaining the turbine at a particular speed that maintains an optimum tip-speed ratio at the given wind velocity. Circuit schematics of selected source interface converters are shown in Fig. 2. Thus, the source interface typically may consist of a power electronic converter consisting of active/passive devices and controllable elements in some cases.

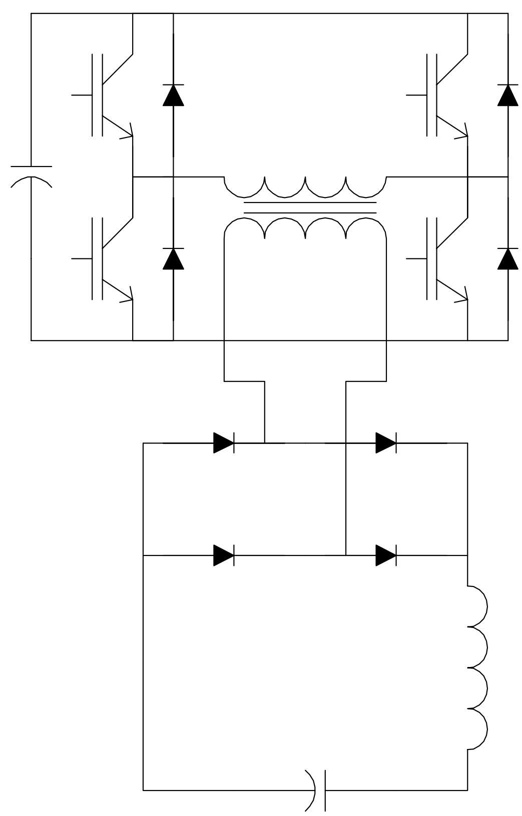

Fig. 2: Schematic of a typical power converter that may be used in Fuel Cell DG system for interfacing between dc bus and the fuel cell

B. DC Bus

The purpose of the dc bus is to provide an intermediate energy storage that buffers the output of the source interface converter and the inverter stage. In its simplest form, it may consist of a capacitive bus. In systems that are more complex, other energy storage devices such as batteries, ultra-capacitors, super-conducting magnetic energy storage coils, etc. may be employed. In such cases, the dc bus may employ a power converter interface to the storage device for matching purposes.

C. Inverter

An inverter is used to convert energy from the dc bus into utility grade ac power at constant voltage and constant frequency. In small residential systems, the output may be single phase ac. Single phase inverters may be of half bridge or full bridge type. In typical industrial and commercial scale systems, the inverter is invariably three phase ac. The three phase inverter may be of three-wire or four-wire output type. Figs. 3 and 4 illustrates the schematic of three-wire and four-wire inverters respectively. In the case of three-wire type, a transformer would be necessary to interface the output to a four-wire ac output system if so desired.

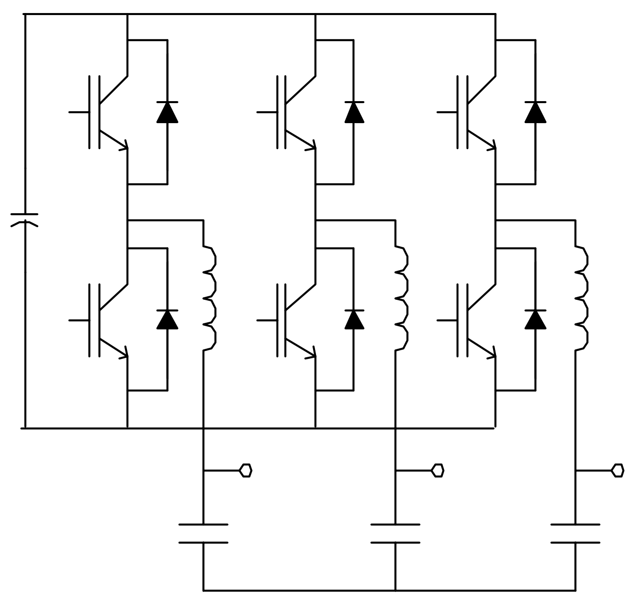

Fig. 3: Schematic of a three wire inverter that may be used in an advanced DG system

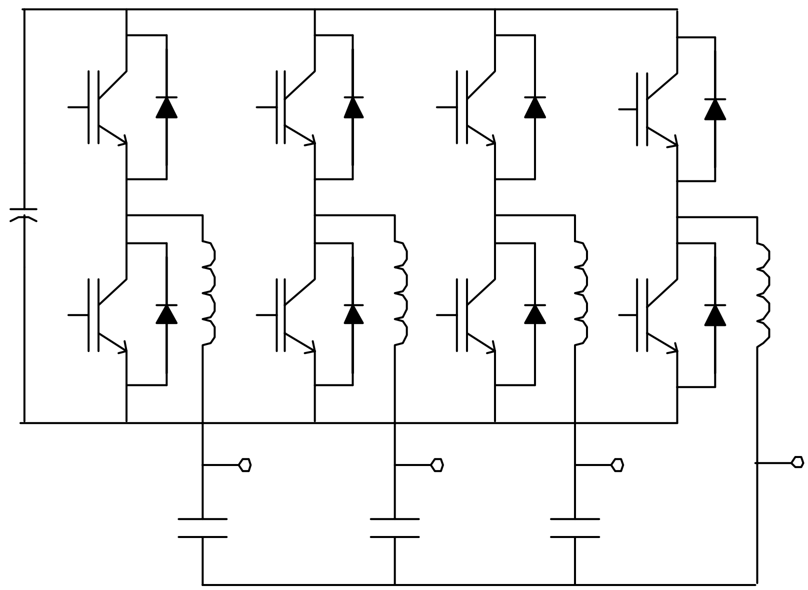

Fig. 4: Schematic of a four wire inverter that may be used in an advanced DG system

In the case of four-wire type of inverter, the interface transformer would be optional. The inverters are typically realized using IGBTs, which are becoming available at several hundreds of amperes at over a thousand volt blocking capacitor, making it convenient to realize high power inverters. Fig. 5 illustrates the schematic of a three phase inverter module that may be used for DG systems.

Fig. 5: Three phase inverter IGBT module that may be used in an advanced DG system(Courtesy: EUPEC Semiconductors)

Although these modules appear to be easy to use and scalable, internally they consist of complex interconnection of several silicon dies wire-bonded together. Fig. 6 illustrates the internal structure of one of the modules, along with a failed wire bond interconnection. One of the major sources of reliability problems in these modules is intimately related to thermal management of the module, which becomes difficult as they become larger.

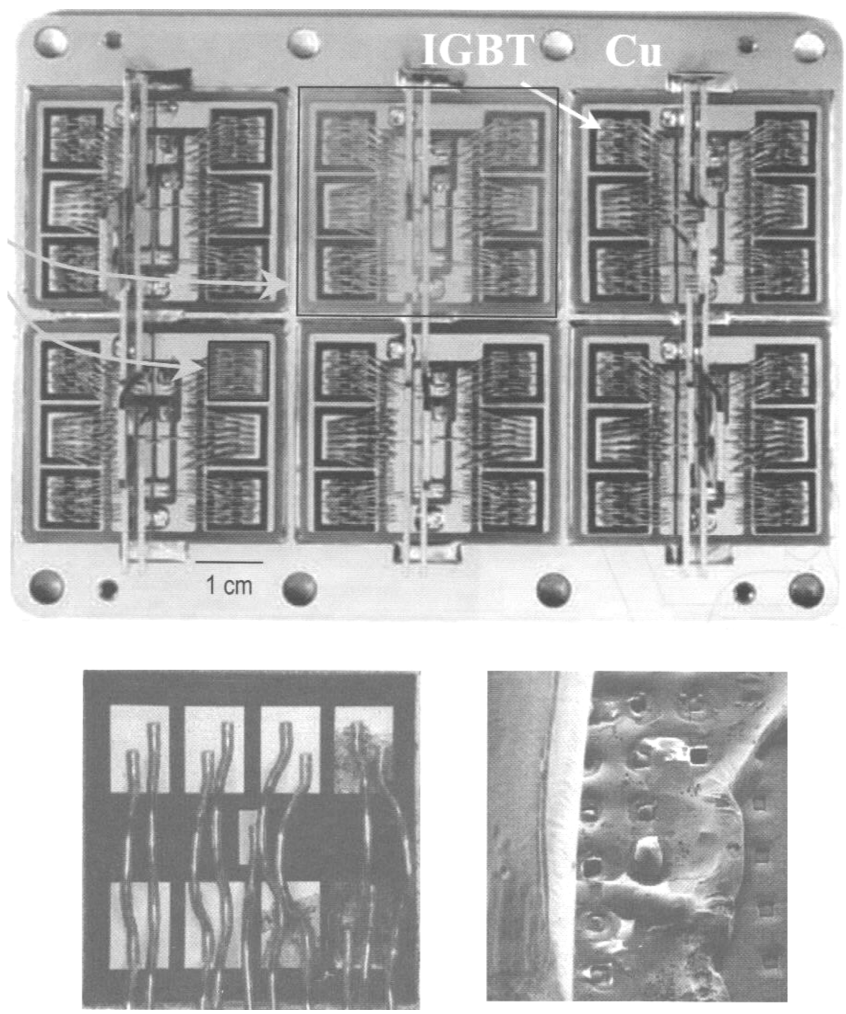

Fig. 6: Internal structure of a typical three phase IGBT inverter module illustrating the number of wire bonds and their failures

Fig. 7 illustrates the thermal map of a module as the device is functioning. The temperature mismatch between various dies in the module is evident. These issues are not only significant for the inverter, but also for the source interface converter. The major focus of the work being performed under the CPES umbrella is to address these issues.

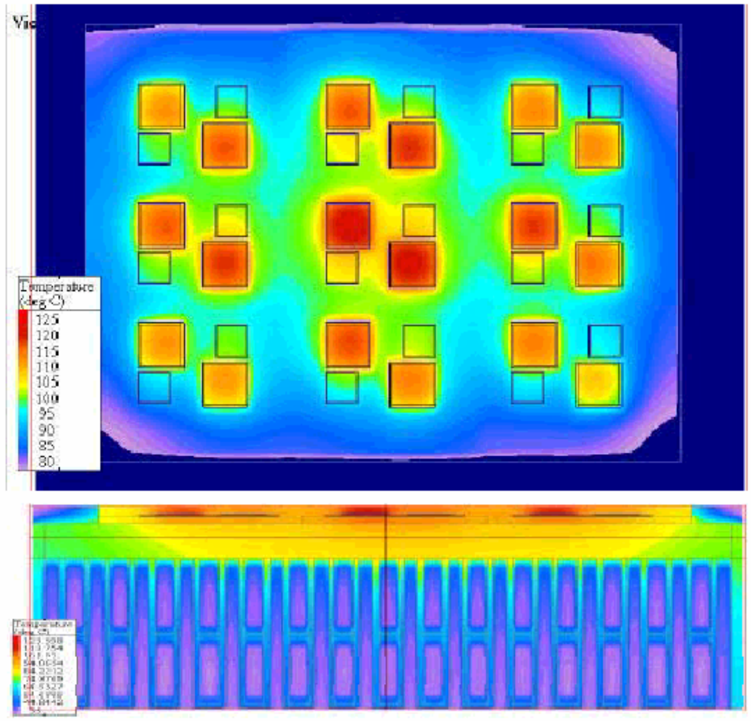

Fig. 7: Thermal map of a three phase IGBT module illustrating the temperature variations within a module (Courtesy: EUPEC Semiconductors)

D. Output Filter

The output voltage from the inverter is typically discontinuous containing a large amount of energy at harmonic frequencies. An output filter becomes necessary to attenuate the switching harmonics and generate utility grade power. The filter is typically of L-C second order type.

E. Interface transformer

A transformer may be applied between the output of the inverter and the point of load to provide electrical isolation and/or four wire output to the load. Typically, a delta-wye transformer is employed. The delta connected primary windings of transformer also absorbs zero sequence currents that may be present on the secondary in case the inverter is of three wire type with no provision to supply zero sequence currents. The transformer may also be K-factor rated in cases where it needs to supply a large amount of harmonic currents.

F. Interface protective relaying

The protective relaying functions in a DG system may be internally provided in the inverter. However, it is also common practice to install separate digital relaying equipment at the interface, especially in conventional DG systems with conventional alternators. The protective relay may perform under-voltage/over-current/under-frequency/anti-islanding/reverse power flow functions and may require its own sensor inputs of various voltages and currents.

G. Switchgear

Disconnect switches and circuit breakers are inherent to isolate the DG system from the grid in case of faults, abnormal operating conditions, scheduled off periods and maintenance. In addition, automatic transfer switches, and static transfer switches may also be used for providing various operating modes and power quality functions.

H. Sensors

Various PTs and CTs may be used for inverter control functions, inverter internal protection functions and for protective relaying equipment. They may also be used for synchronization functions.

I. System Control/Software

Control of an advanced DG system that consists of an inverter and other dc-dc converters is quite complex and typically accomplished using Digital Signal Processing (DSP) systems. However, this would be at the lowest level of hierarchy, operating at the core level of the system. The control function necessary for user interface is typically implements through an RTU.

J. Interconnections

Thus, a typical advanced DG system is a complex electrical system consisting of numerous components parts, each of which has its own packaging aspect ratio, electrical terminations and thermal management requirements. Fig. 8 shows the disconnected view of a state of the art inverter system. The complexity of the interconnect system is quite clear from the figure. In comparison, a conventional alternator driven by a fossil fuel engine appears simple, even including the field regulator. The interconnections between these diverse components electrically and mechanically in a package requires a considerable amount of engineering effort. After the outlay of considerable engineering design effort, one is left with a system that has poor manufacturability attributes. Even beyond the manufactured product, the reliability of the system suffers due the numerous interconnections and poor maintainability. A more recent packaging concept is illustrated in Fig. 9.

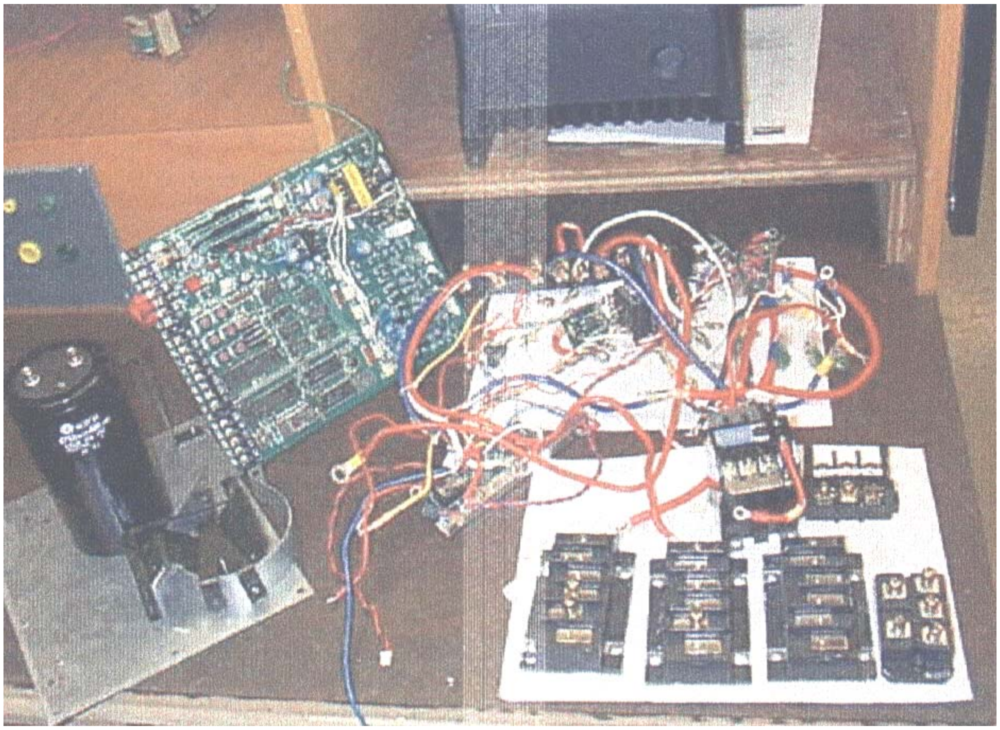

Fig. 8: Disassembled view of a typical state of the art inverter used in a DG system

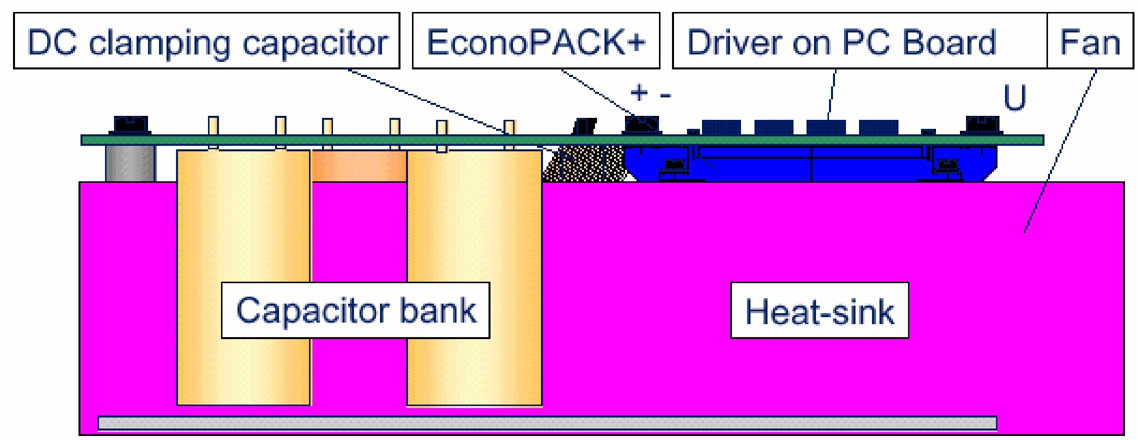

Fig. 9: A recent packaging concept for inverters using high power IGBT modules (Courtesy: EUPEC Semiconductors)

Overall, advanced DG systems of today's art leave a lot to be desired. A majority of current developmental efforts is generally focused on advancing individual component technologies and not at making a coordinated effort at managing the complexity of the system. It is felt that until the issue of complexity of the interconnection among BOS components are managed, low cost highly reliable power electronics systems will remain a difficult problem to crack. It is on this premise that the present task is being focused on developing a coordinated approach that is coherent with the efforts of CPES' efforts on developing IPEMs. A schematic of a conceptual IPEM module that eliminates the wire-bonds and integrates the thermal management, gate drives and protection functions as envisioned by CPES is illustrated in Fig. 10.

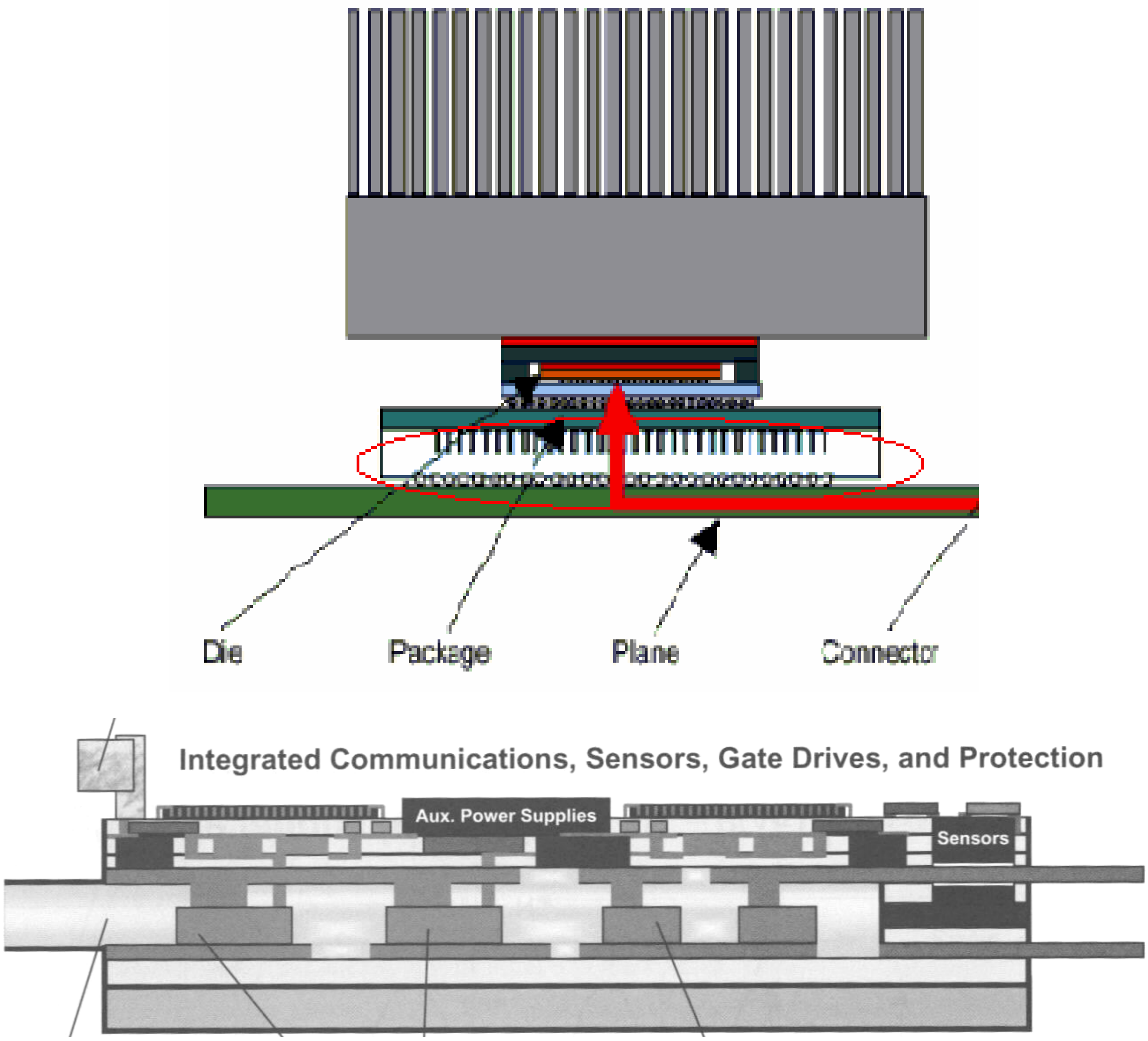

Fig. 10: Conceptual schematic of an IPEM module

The "Bricks and Buses" concept described further in the following chapter is aimed at addressing the realization of power electronics systems using IPEM modules.

3. The "Bricks & Buses" Concept

Typical power electronics design involves innumerous trade-offs in the areas of application, topology, semiconductors, reactive components, controls, sensors and interface circuits, control software, thermal management, packaging, manufacturing and testing. However, as new generations of designs evolve, the creative design improvement processes have typically been heavily fragmented, resulting in innovations in various areas being driven independently without common benchmarks and visions. Most improvements in performance can be generally traced to the introduction of new semiconductor switches. The evolution of power semiconductors that has driven the power electronics industry over the past century is illustrated in Fig. 11.

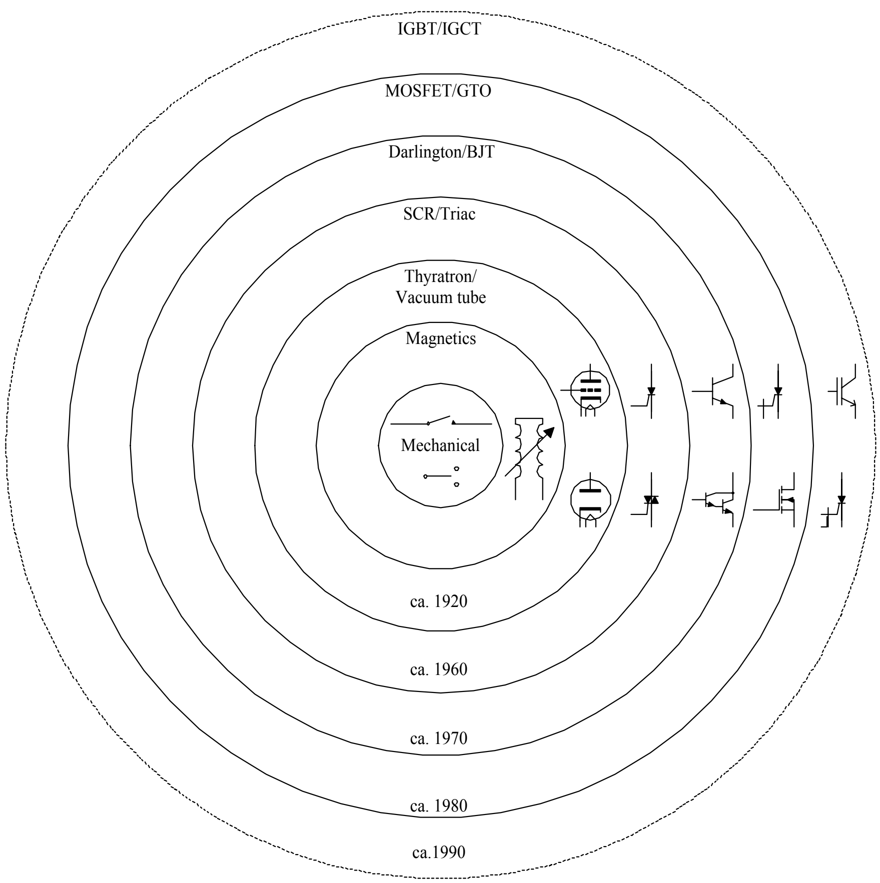

Fig. 11: Evolution of power semiconductor devices over the past century

To be sure, the introduction of new power semiconductors has resulted in expansion of their application arena. However, we have not seen an explosion in product opportunities as has happened in the digital electronics field. This scenario in the power electronics industry today is strikingly similar to the state of the digital integrated circuit industry before the onset of the VLSI revolution [4]. A vision of highly integrated architectural framework was developed by the VLSI industry at that time, which dissolved the boundaries between functions, circuits, simulation, prototyping, manufacturing, testing, etc. Fig. 12 illustrates a state-machine oriented model for a digital computer that has typically been the basis for design before the advent of the VLSI revolution.

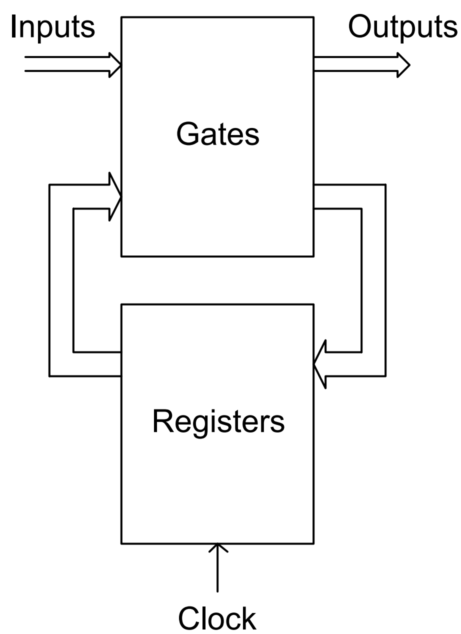

Fig. 12: A state-machine oriented view of a digital computer

Fig. 13 illustrates a bus-oriented architecture that was made popular by the microcomputers that led to the VLSI revolution. The bus frequency dictates the parameters of all the constituent technologies that comprise the system. The acronym VLSI may be construed to refer to more abstract levels of integration beyond having numerous circuit elements on a common substrate – it represents a vertical integration of domains of engineering activity such as system design, logic design, circuit component design, geometric layout design, interconnect design, device fabrication process, device packaging, manufacturing, etc. One of the first successful devices to utilize such an integrated framework was a simple four-bit general-purpose microprocessor. It resulted in an information-processing device, which was primitive when compared to the minicomputers of that day. However, the framework was powerful enough to lead to the rapid evolution of technology following the famous Moore's law. Today, the creative value-adding activity chain down to the level of marketing and customer relationships continue to be integrated within the framework.

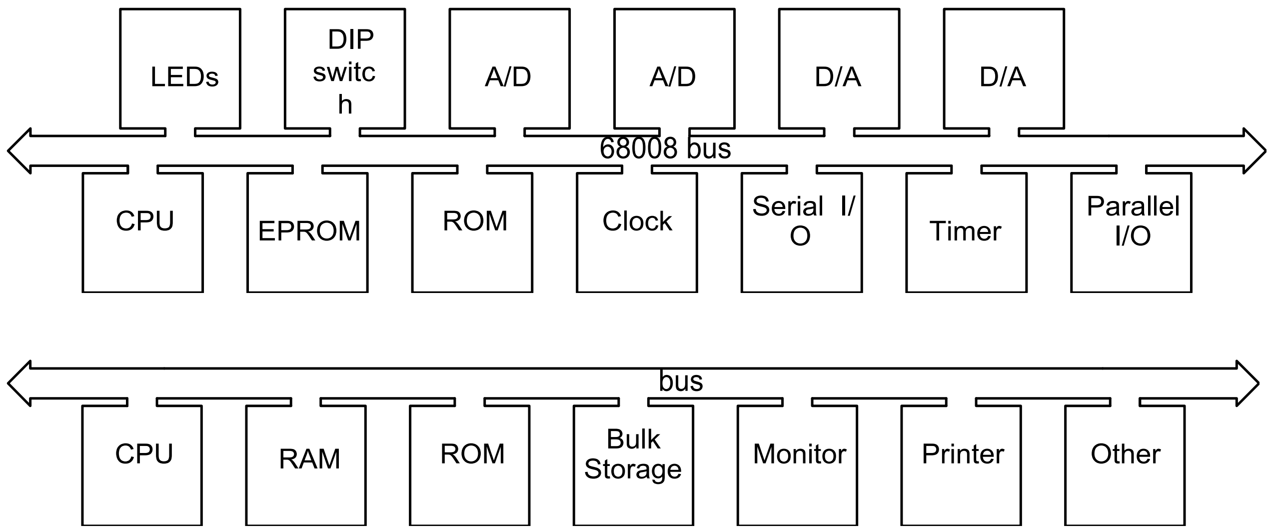

Fig. 13: A bus oriented view of a digital computer

It is felt that the field of power electronics also could follow a similar course, if a common framework is laid out and the vision is shared by the stakeholders of the technology. A modest beginning for developing an abstraction of principles involved in a power electronic system that can lead to such an integrated framework is presented in this report.

The benefits of such a highly integrated framework will be reduced design effort, modular realization, hierarchal organization, shared road-mapping, targeted technology development, standardized manufacturing protocols and specifications. Moreover, as the applications development process becomes less complex and driven by software professionals, it will lead to the unshackling of creativity and the application areas become rich and diverse, as is true in the information processing industry today.

An integrated framework for topological realization and analysis of switching power converters have been put forth long ago by P. Wood in his classic text on switching power converters [5]. More recently, coordinated interconnections have been proposed to streamline the process of interconnection in power converters [6]. However, these attempts stop short of making the critical associations between the circuit topological level to the geometric architectural level and result in a unified architectural foundation to build upon.

The concepts and ideas presented here are not entirely new and a close parallel with various efforts presented by the champions of Power Electronic Building Blocks (PEBB) and the Center for Power Electronics Systems (CPES). However, the inspiration for the approach here has been derived from the classical Japanese House Architecture [7,8].

In the proposed vision of power conversion engineering activity, the designer envisions a particular application and develops a realization for the power converter using a Computer Aided Design (CAD) environment. In the design environment, the designer is able to select different constituent elements and graphically integrate them to develop the functional topology when realizes the objective at hand. The most important feature of the proposed vision is that at this stage, the three dimensional geometry of the physical layout is explicitly determined concurrently with the functional specification. The electrical circuit design process and the mechanical package design are seamlessly integrated. Once the solid geometry of the design including the materials and processes are designed, the CAD design environment is able to compute performance attributes in various domains of interest and allow the designer to iterate the design. After the designer is satisfied with the performance, the output of the CAD system is shipped to the prototyping house/foundry for manufacturing the product.

The proposed approach (Fig. 14) is built around system of various bricks and buses. The geometrical dimensions of various "brick" components are standardized, much in the manner of NEMA frame sizes or DIP IC packages.

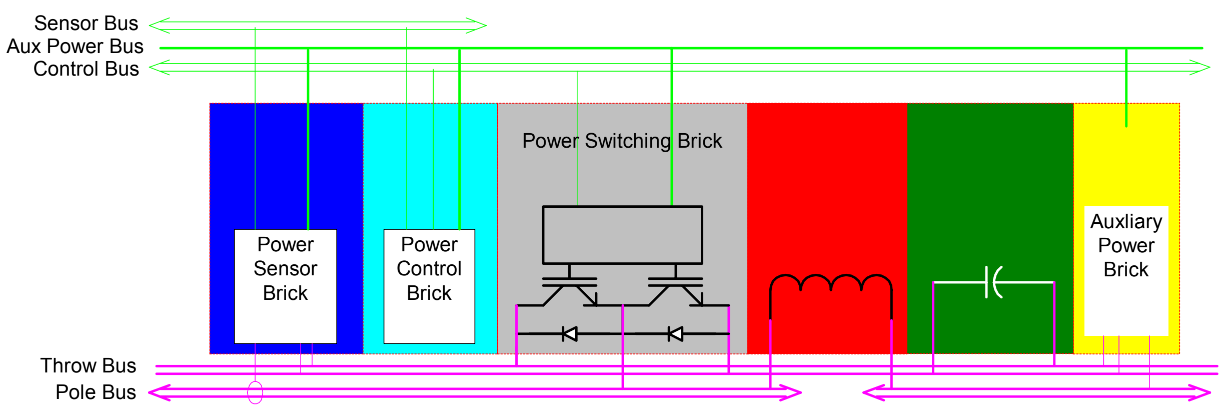

Fig. 14: Illustration of the Bricks & Buses concept of power converters

The depth and the height of brick are fixed, (say a few inches) whereas the width may be variable in smaller increments (say a half inch). In this manner, any given component that forms the power converter can occupy an appropriate volume as necessary to fulfil its scaling behavior. Each brick is self contained from the point of view of thermal management. One face, (say, the front face) of all the bricks contain the power interconnection tabs at standard increments. Another face (say, the rear face) of all the bricks contains all the control, housekeeping power and signal level auxiliary connection pins.

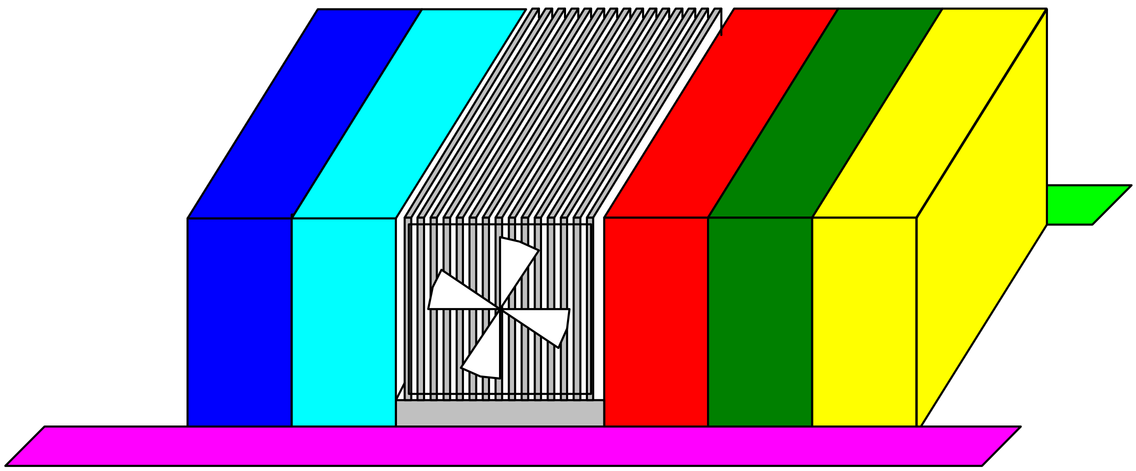

Fig. 15: Illustration of the Bricks & Buses realization of power converters

In order to realize a power conversion system, various bricks are stacked together on a rack or a suitable frame. The “buses” are then added to the stack of bricks to make the interconnections. A multilayer busbar that has been specifically configured for the given application realizes the power circuit. A printed circuit board or a cable interconnection system, soldered to the signal connection face to realize the signal bus.

Different functional units that make up the brick of any power converter may identified as Power Switching Brick (PSB), Power Control Brick (PCB), Current Stiffening Brick (CSB), Voltage Stiffening Brick (VSB), Sensor Device Brick (SDB), Auxiliary Power Brick (APB), Input Output Brick and Auxiliary Utility Brick (AUB). The buses that consitute the Power Bus Assembly (PBA), Control Bus Assembly (CBA). The PCB contains the Power Processing Software (PPS) necessary for controlling the various bricks using the various buses to realize the desired power conversion function.

In certain cases, the bricks may include local status information intelligence such as voltage, current, etc. In such cases, the brick may be considered "smart". The sensor output information is available in appropriate digital format for use by the controller. The information may include temperature, lifetime and other information, which may be useful for the entire system.

A. Power Switching Brick (PSB)

The PSB represents the muscle of the proposed framework, directing energy flow as desired by the process. Typically, each PSB is a Single Pole Double Throw (SPDT) switch, with unidirectional voltage blocking and bi-directional current carrying capacity. This is essentially a half-bridge module that represents the building block of various inverters. Each PSB has a unique address representing its connectivity to particular pole and throw bus lines. Several PSBs may have a common address, if they are required to perform synchronized switching functions, either operating in parallel or series. Each PSB may contain integrated gate drives, isolated power supply, isolated signal interface, protection and thermal management functions built into the unit, along with address decoding and other interface logic necessary to communicate with the control bus. It may receive auxiliary power as high frequency ac for isolated gate drives and a low power dc for logic functions. When a particular PSB device's address is selected and the communication is enabled, the PSB executes the switching command from the data bus. It provides status information to the control bus upon request. In certain applications, the PSBs may incorporate decoupling bus capacitors, snubbers or other means of soft-switching networks within them.

B. Power Bus Assembly (PBA)

Various power circuit connections to and from various bricks are made through one of the lines of the PBA. Each line in the PBA may carry a stiff current or a stiff voltage. Examples of stiff currents may be the phase terminal of a three phase induction motor or a terminal of the filter inductor current of a full bridge buck converter. An example of a stiff voltage is the terminals of the dc bus voltage of a voltage source inverter. The PBA will consist of a multilayer bus bar with bus connections at specified intervals. However, the connectivity between various terminals may be determined to meet the requirements of the power conversion function.

C. Voltage Stiffening Brick (VSB)

Capacitive filters may be connected in shunt across throw bus lines or across the throw terminals of the PSB to stiffen the voltage. They may also perform absorbtion of harmonic currents in shunt. Bricks that are more complicated may contain higher order elements such as a Π section filter.

D. Current Stiffening Brick (CSB)

Inductive filters may be connected in series with a pole bus, between the pole terminal of the PSB and a load or source device to stiffen the current. Bricks that are more complicated may contain T section filters for current stiffening.

E. Power Control Brick (PCB)

The PCB forms the brain of the proposed framework. It is a programmable device, capable of coordinating and channeling power flow by communicating to various PSBs through the control bus. The embedded software in the PCB develops and executes the switching functions necessary to effect the desired power flow. It receives feedback and feed-forward information necessary for the process from various sensor units. Communication between the PCB, PSB and various other bricks may follow a common communication protocol such as the Control Area Network (CAN) to realize efficient flow information.

F. Sensor Device Brick (SDB)

Various SDBs in the system may be used to sense current, voltage and other signals. They may evolve to become "smart sensors". The signals may be provided in the digital form for the PCB upon request. The PSBs communicate with the PSBs using the sensor bus, which has the required number of data lines and address lines to accommodate the number of devices. The PSBs may use explicit sensors, or may derive the quantity using various observers or state estimators to obtain the necessary quantity of interest to the PCB.

G. Control Bus Assembly (CB)

The control bus may be subdivided into Control Address Bus (CAB) lines, Control Data Bus (CDB) and other control lines such as enable lines, status flags, interrupt lines, and shut down lines. The number of CAB lines depends on the number of independent PSB and SDB devices required. For instance, a three phase in, three phase out, PWM rectifier/inverter system will have six independent PSB devices, two phase current sensors and one dc voltage sensor. This represents a total of requiring 9 address locations, which can be served by a four bit address bus. The data bus typically will contain as many bits as necessary to represent the PWM and sensor data information. On the other hand, the entire control and communication process could use a

CAN type of serial interconnection protocol with distributed intelligence at each of the bricks. In this case the entire communcation can be realized using two conductors or a fiber optic channel.

H. Auxiliary Power Brick (APB)

The APB provides a high frequency ac power supply system for isolated gate drive units and a dc power system for logic circuits used in the power conversion system. It may receive its primary power from either the pole bus or the throw bus depending on the application.

I. Housekeeping Power Bus (HPB)

The HPB carries the auxiliary power lines to the various bricks from the APB.

J. Auxiliary Utility Brick (AUB)

Realization of the power converter typically requires a number of other elements such as inrush current limiters, EMI filters, circuit breakers, etc. Most often, the interconnection and package design overhead required for these balance of system elements are significant. Ideally, the geometry of these elements will also fit into the Bricks and Buses framework presented here.

K. Input Output Brick (IOB)

The IOB will contain the interface circuitry necessary for interfacing the power converter with the external world.

L. Power Processing Software (PPS)

The PCU will have a programmable feature wherein common power processing routines such as pulse width modulation, current regulation, PI control, etc. may be implemented in a modular fashion using a high level language, HTML or a graphical interface. The resident software will have a high level instruction set for performing PWM and other common primitives.

4. Technology Features

Using the Bricks & Buses concept, power converters of varying functions can be integrated with ease. Fig. 16 illustrates the realization of a three phase ac input to three phase output system that would be common in a DG system using microturbines using the Bricks and Buses concept. Fig. 17 illustrates the realization of a full bridge dc-dc converter that would be common with a photovoltaic system or a fuel cell system. However, there are several critical technological processes to be developed to enable the realization of the proposed framework.

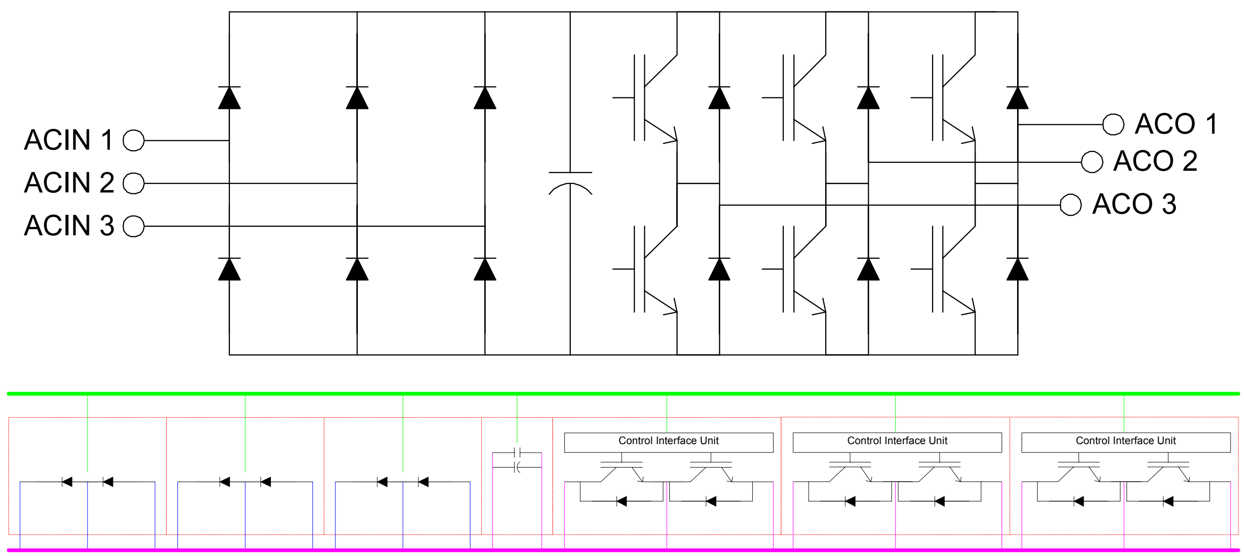

Fig. 16: Realization of a three phase-three phase power converter using Bricks & Buses concept

It is obvious that the technology development has to follow a top-down approach. At present, advances in power electronics and particularly in packaging are driven from the bottom. As a result, development of a shared vision which drives the technology roadmap that is essential to the development process itself, is not common practice. Arguably, initiatives such as ONR's PEBB program are only beginning to have incremental impact upon the industry.

For instance, the aspect ratio of various components such as IGBT modules, intelligent power modules, capacitors and inductors that form power converters are richly various and seldom match each other. But there are rare exceptions – connector geometry and spacing for certain dc bus decoupling capacitors matched with the connector spacing for IGBT power modules. Such shared technology development process is common in the digital computer industry – for instance, development of high speed memory chips to interface with high speed processors. It is rather interesting to note that the power electronics industry as a whole participates in the shared digital technology development roadmap with enthusiasm (and equal regret) – for instance low voltage dc power supplies for the processor.

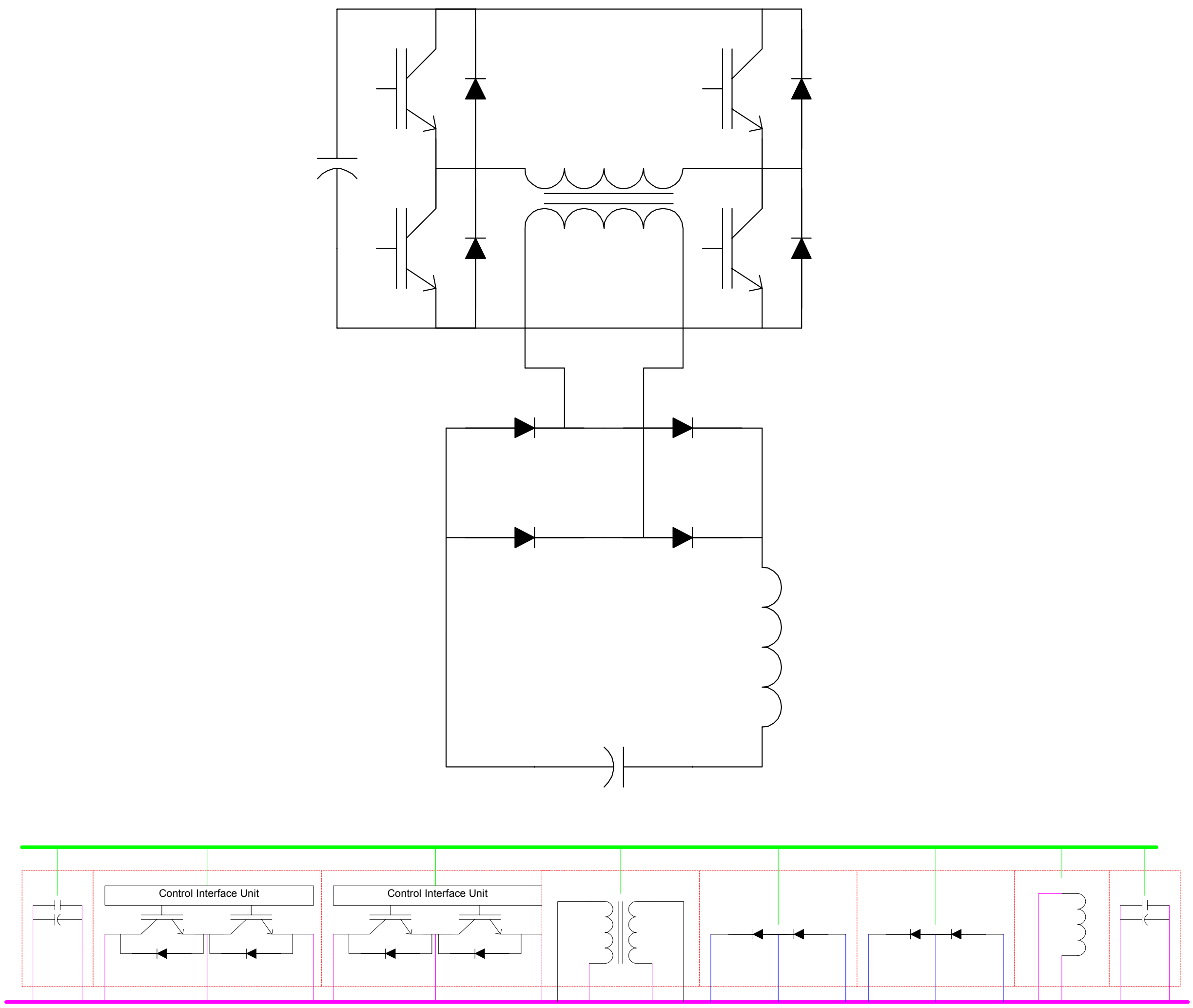

Fig. 17: Realization of a full bridge dc-dc power converter using Bricks & Buses concept

A brief discussion of various technology elements and processes involved in the proposed framework are presented further. At the topmost level of the heirarchy lies the development design rules that constrain the size of the bricks and buses. The design rules should be flexible enough to accommodate the peculiraties of the functional requirements of the bricks and buses and minimize the parasitic efects. They should accommodate the cooling loads required by the functional elements that compose the brick.

The primary scaling parameters of the physical system will be the power throughput and the maximum switching frequency. Secondary variables such as device transition periods, parasitic inductance and capacitances, power loss, cooling technology, capacitor technology, etc., are expected to play a role in determining the geometry, once the power throughput and maximum switching frequency are determined. The similarity in the VLSI industry may be clock frequency and device voltage of microprocessor.

When the bricks are assembled together, they are aligned along the faces with identical section. Thus, two of the faces of the bricks typically face other bricks, and hence may not be available for other purposes, for instance, cooling. Ignoring the unavailable faces, as a number of bricks are arranged together, the amount of surface area available for heat rejection and/or other purposes increases in proportion. Hence, as the width of the brick increases, for instance to accommodate higher voltage and/or current levels, the volume of the brick and the surface area available for cooling increases in proportion. This typically enables control of hot spot temperatures better than increasing all linear dimensions incrementally.

The multilayer power bus contains all the power flow paths in a single intimately coupled electromechanical assembly. Since all the current flow paths are geometrically assembled with minimal enclosed area, the EMI radiation from the converter is at the lowest. Moreover, the signal buses are geometrially isolated from the noisy power flow buses, and hence do not suffer from internal cross coupling. Through judicious placement of the control bricks at appropriate locations, the electromagnetic coupling into the control circuit can be minimized further.

Arguably, among the various bricks that constitute the proposed framework, the vision of the PSB is further along than the rest. The functional vision has been realized through intelligent modules and skip modules from various manufacturers and initiatives to eliminate the unreliable and cumbersome wirebonds with flip-chip and power overlay technologies are being developed at various research groups. Integration of a self contained cooling mechanism with each module would represent the logical step to evolve the present vision into the proposed framework. To a large extent, integration of a minimal amount of decoupling capacitors and primitive snubber modules may also enable improvement in the performance of the PSB, especially with respect to EMI.

Multilayer film, wound film and multilayer ceramic capacitors have been available in cubical geometries readily. However, electrolyric capacitors are primarily found in cylindrical cans, and hence will be difficult to fit in the proposed framework. Transformers and inductors in cubical geometries are commonly found in planar magnetic technologies and matrix transformers, which may be adapted to fit in the proposed framework.

Other brick elments such as sensors, auxiliary power supplies and control circuits may be readily packaged into a cubical form using appropriate enclosures. Auxiliary bricks such as switchgear and other protection elements may require adapters to enable them to fit in with the proposed framework.

The realization of multiple converter units connected in a modular fashion to increase the power throughput further beyond the first hierarchal level is illustrated in Fig. 18.

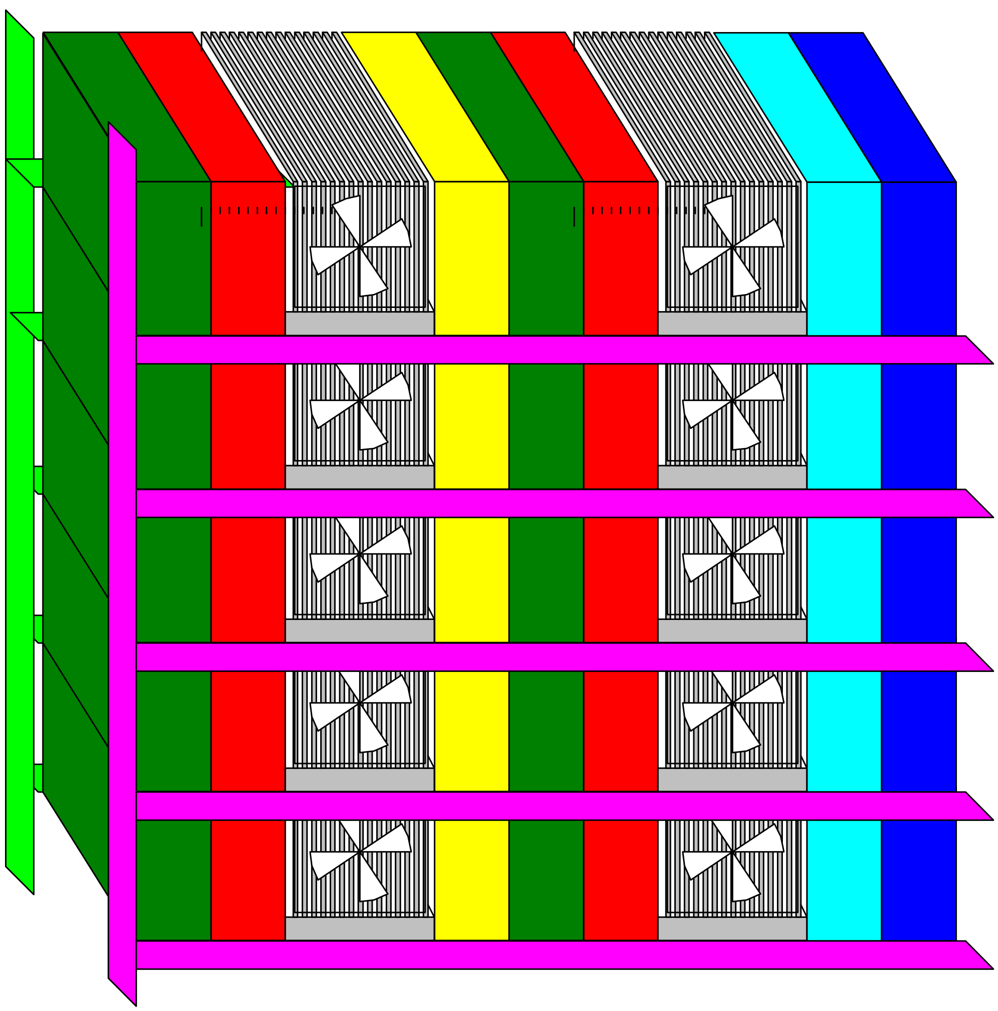

Fig. 18: Realization of multiple converter units modules to scale the power level

5. Design Tools

In generally, design of power electronic systems involves numerous trade-offs as is common in most engineered systems. It proceeds through a careful selection process for various parameters and technologies starting with the electrical design and culminating in manufacturing process design. The electrical design process leading to the selection of power electronic circuit components is mature and well established. However, rendering well-conceived electrical designs into reliable and low-cost products suitable for widespread application requires a substantial amount of additional engineering effort. The physical design proceeds further beyond the electrical design, accounting for trace current densities, die-attach processes, dielectric isolation requirements, semiconductor power losses, thermal management methods, thermo-mechanical stresses, electromagnetic interference, etc. Aforesaid factors that affect the design are coupled through complex interrelationships. Design activity encompasses several engineering domains including electrical, thermal, material processing and manufacturing sciences. Traditionally, these conditions lead to a serial approach towards product design and development. Issues related to electrical design, materials selection, mechanical layout, EMI, thermal management, manufacturing process development, reliability and cost strategies are addressed sequentially and often sadly in an isolated manner. By nature, such a serial process is plagued by concealed and competing trade-offs, which obscure the path towards an optimal solution. Unfortunately, it is virtually impossible to make objective design decisions based on unified analytical solutions. Nevertheless, as economic pressures to increase the performance/cost ratio keep mounting, the need for a better understanding and visualization of the design space is being felt. It is therefore crucial to fill these gaps in knowledge and integrate them into the power electronics design process. Only then, can modern enterprise practices like integrated product and process development can be successfully applied to the field of power electronics, leading to further cost reductions and performance improvements. This fundamental issue in power electronics needs to be addressed through the development of system-level evaluation tools to analyze the effect of various design choices that extend beyond traditional engineering domain boundaries.

In order to fulfill this goal, it is clear that we need to describe the numerous relationships among the power converter design features and various design parameters mathematically, so that product and process design parameters can be optimized. Most of existing literature describing such relationships is scattered across various diverse disciplines that include electron devices, material science, electromagnetics, thermodynamics, and fluid dynamics. The analytical and empirical models that are found in these fields of study will have to be integrated together on a common platform. Applying the models from diverse sources to the field of power electronic systems will invariably require the variability functions to be extrapolated. In several instances, the relationships between the parameters and performance may be unknown. In such cases, experimental and analytical investigations to develop the relationships or to confirm the validity of the extrapolation will have to be identified. The models will be useful to uncover the various cross-coupling mechanisms that affect the physical realization of a power converter. They will provide a platform to study the cause-effect relationships among various design selections in a unified manner.

The primary parameters of such a scaling study would be the power throughput and operating voltage of the power converter. However, given the primary scaling parameters, several physical quantities play a role in determining the physical realization of the power converters. Design parameters may be identified for various components and constituent technologies including: power semiconductor die area, switching speed, conduction voltage drop and current density; interconnect material, width and thickness; heat-spreader thickness, coefficient of thermal expansion and area; etc. Each of these quantities affects each other through complicated and often subtle relationships. For instance, the switching speed of the device determines the propagation of the electromagnetic wave along the interconnection. Therefore, it plays a role in the selection of geometry of the interconnection. In order to manage and control the EMI induced by the traveling electromagnetic wave, EMI control components are introduced along the interconnection path. The interdependence of such design variables on the overall performance characteristics will have to be quantified and a coupled mathematical model should be developed during the project.

In the past, time domain simulation tools and finite element computational tools have been used extensively and almost exclusively for design verification in electrical, thermal and other physical domains. These tools are efficient in providing valuable verification of designs after the designs are complete. However, they are of little practical assistance in the broad decision making process during the design process due to the tediousness of the simulation process, the impracticality of performing what-if analyses, and a lack of cross-domain simulation tools. Fourier transform methods in the temporal and spatial domains can be used for systematically partitioning the analysis problems in electrical and thermal domains respectively. Although these techniques are available in the literature for several years, they have not been used for system level analysis in the past. Such methods are computationally efficient for obtaining sensitivity functions and capable of illuminating broad design trends rapidly, when compared to tedious time-domain simulation models and finite element analysis tools. These techniques could be used in conjunction with piecewise-linear behavioral models for power devices and components as opposed to complete physics-based models. Behavioral models can be readily determined through numerically justified analytical approximations of physical models and through simple experiments. A comprehensive analytical system-level evaluation tool incorporating models that capture the essence of cross-coupling between the design variables while remaining simple enough will assist designers to establish broad design philosophies in the initial stages of the product development process. For instance, the tools would make it easier to answer questions like, "Under what conditions is it beneficial to integrate decoupling capacitors inside a power module, as opposed to interconnecting it separately?"

An integrated design environment has to be developed which enables the process to proceed from the concept definition stage through manufacturing. The graphic oriented design stage should be able to take the geometrical arrangement of bricks and buses and predict the performance in terms of electrical, mechanical, thermal, EMI, life time and cost performance indices. The designers should be able to iterate the designs on an automated manner. Once the design is satisfactory, the design files, which describe the bricks and buses in a particular format, may be used by a computer integrated manufacturing process to physically realize the converter. Such a graphical design environment that is under development is illustrated in Fig. 19.

Coupled with the physical design process, the software that drives the converter switches will also need to be developed. For this purpose, an alternative paradigm for converter control based on "digital power processing" needs to be developed, which deals with the converter operation in an entirely abstract sense in terms of energy transfer. The principles of abstraction necessary for this is being developed are at present.

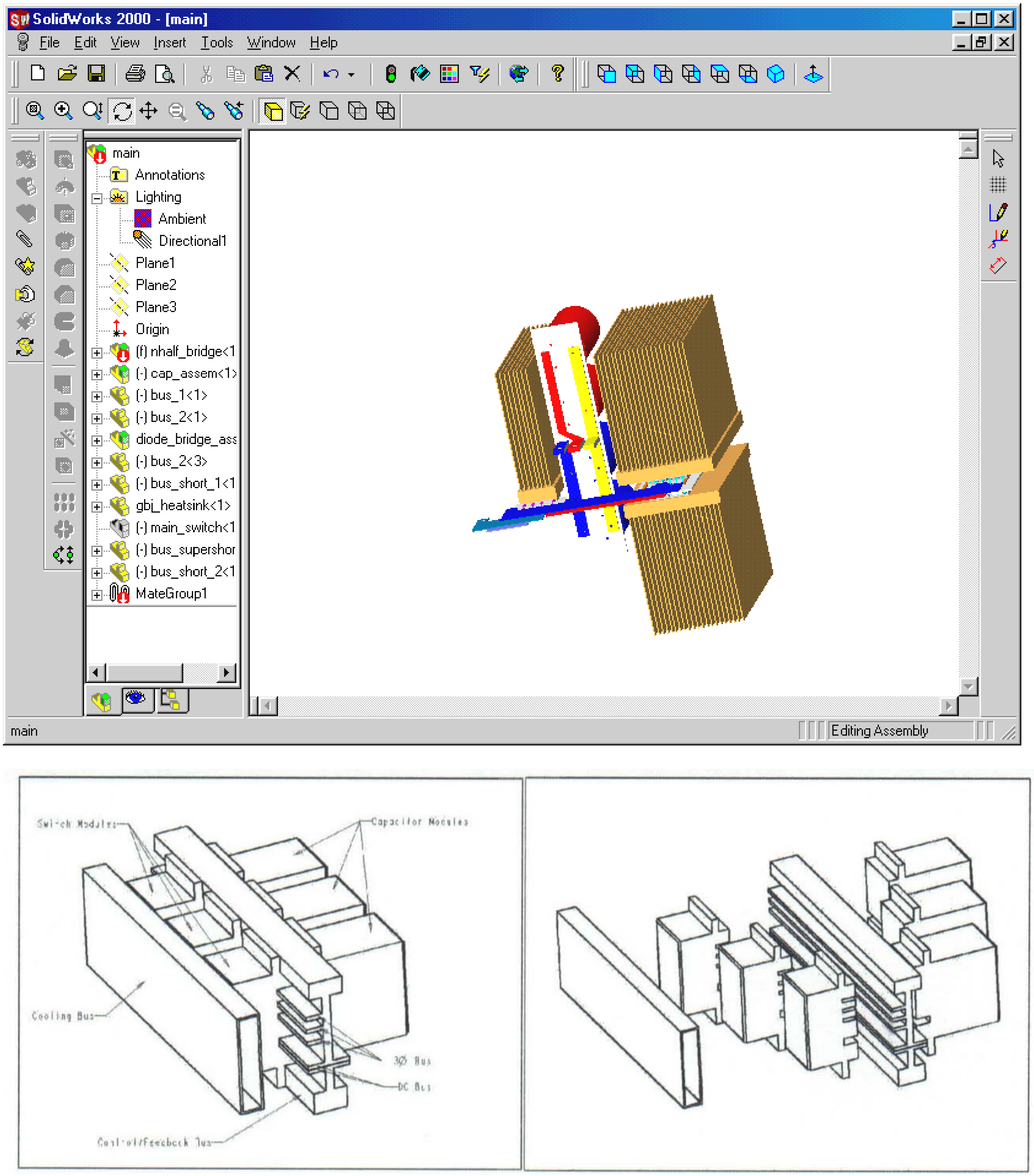

Fig. 19: A graphical design environment for development of power converters using Bricks and Buses concept

Any approach towards a general purpose framework as being proposed here will have to be evaluated in terms of cost and performance in comparison with conventional application specific design which is common practice today. Recently an approach to performing such an evaluation using a value engineering study involved in integrating a motor drive and a power converter in presented in [5]. However, such studies are more easily done in product specific scenarios. The premise here is that the application domain and markets of power converters will expand rapidly to justify the infrastructure necessary to support the proposed framework.

6. Conclusions

This report has presented an integrated framework for realization of power electronic converters for use in distributed generation systems. Typical functional component elements that constitute advanced DG systems have described along with state of the art means for realizing these functional elements and their technology trends. The Bricks & Buses concept has been presented as an alternative to present day application specific design of power converters. The concepts represents a modular architecture of realizing DG systems in particular and power electronic systems at large is presented. Various critical technology elements that constitute the proposed approach and the development activities necessary to make the approach viable have discussed. The challenges involved in developing design tools for the proposed approach have been detailed.

Prototype systems based on the Bricks & Buses are being built as the abstractions involved in the proposed concept are being translated into concrete manifestations, in both software and hardware.

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